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TITLE: Automated Assessment of Postural Stability (AAPS)

PRINCIPAL INVESTIGATOR: Iyad Obeid, PhD

CONTRACTING ORGANIZATION: Temple University of the Commonwealth System
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14. ABSTRACT

The purpose of this research has been to develop a mobile motion capture system that is capable of quantifying a person's sense of balance, which can in turn be used as a proxy for assessing concussion or musculoskeletal injury. During this research period, we have developed (1) a baseline system based on the Microsoft Kinect motion tracker, (2) a graphical user interface, and (3) algorithms of automated balance scoring. Furthermore, we have begun the process of testing with human volunteers and used our preliminary data to quantify system calibration and limitations of performance. We have also compared our system's performance against that of human experts and determined that our system is in general more reliable.

15. SUBJECT TERMS

motion tracking, balance assessment, Microsoft Kinect, concussion assessment

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Introduction

The purpose of this research has been to develop a mobile motion capture system that is capable of quantifying a person's sense of balance, which can in turn be used as a proxy for assessing concussion or musculoskeletal injury. During this research period, we have developed (1) a baseline system based on the Microsoft Kinect motion tracker, (2) a graphical user interface, and (3) algorithms of automated balance scoring. Furthermore, we have begun the process of testing with human volunteers and used our preliminary data to quantify system calibration and limitations of performance. We have also compared our system's performance against that of human experts and determined that our system is in general more reliable. This report describes performance during the first of three years.

Keywords

motion tracking, balance assessment, Microsoft Kinect, concussion assessment

Accomplishments

What were the major goals and objectives of the project?

The purpose of this project is to create a portable system for assessing balance in armed forces personnel that can be administered in the field with minimal training. Although there are many reasons for assessing an individual's sense of balance, our project focuses on balance deficits caused by concussion, traumatic brain injury, and musculoskeletal injury, since these are especially relevant to fitness for duty. Our deliverable will be a stand-alone system comprising a Microsoft Kinect motion tracking system and a dedicated laptop personal computer running custom software for data acquisition and analysis. The system is called the Automated Assessment of Postural Stability, or AAPS.

The project is designed around four Specific Aims, or goals:

1. Develop Baseline AAPS System
2. AAPS Calibration and Baseline Evaluation
3. AAPS Field Evaluation
4. Develop Expanded xAAPS Test

What was accomplished under these goals?

Year 1 was devoted to building the baseline AAPS system, calibrating and testing it, and establishing and beginning balance testing with human subjects. The AAPS system is essentially a completely computerized version of the Balance Error Scoring System (BESS) which is a standardized test for assessing balance that is administered and scored by a human expert. The software for the baseline system is complete, including the design of a graphical user interface, and a back-end system for storing and organizing test data. In addition to developing the baseline system, we have also designed the specific data collection protocol, and received approval from both Temple University IRB and ORP-HRPO. We have initiated data collection with healthy subjects in two phases. In the first phase, subjects performed a series of generic kinematic movements and balance assessments while being tracked simultaneously by the Kinect and a state-of-the-art motion capture system. This allowed us to quantify the limitations of the Kinect's motion tracking ability, which will be critical for calibrating the AAPS in the future. The second phase of subjects are our "core" group who perform the BESS balance test while the AAPS system records and scores performance. These "core" data are also being used to compare human BESS scoring

to computerized AAPS scoring in order to determine AAPS performance relative to human inter-rater agreement.

We were also successful in establishing a working relationship with the Temple University ROTC and with caregivers at the Philadelphia VA Medical Center. We conducted three in-person meetings (2 February, 2 May, and 23 May 2016) to explain the project, solicit input, and establish the parameters for working together in the future for data collection and field testing.

<u>Technical Details</u>

The AAPS system has been developed in the C# programming language in the Microsoft Visual Studio 2015 programming environment and the .NET framework. The system includes a comprehensive graphical interface (GUI) to guide the operator and the subjects through the BESS test. It also provides user controls, data management features, a real-time display of the detected body and intuitive visual feedback on the AAPS tracking capabilities. Furthermore, the GUI has been designed to be user-friendly and its use only requires minimal training and experience. The current AAPS GUI is shown in Figure 1.

The AAPS system utilizes an inexpensive Microsoft Kinect v2.0 motion capture sensor and a custom designed software suite for Microsoft Windows to objectively track kinematics during the BESS test. Set-up time is minimal, and no additional calibration time is required. These features make the AAPS a valuable balance assessment tool to be utilized in the field. It only requires the patient to assume the right stance and the system starts extracting tracking information from the sensor data stream and uses a GUI to display the tracked skeleton. By using some simple visual feedback features, the system provides the user

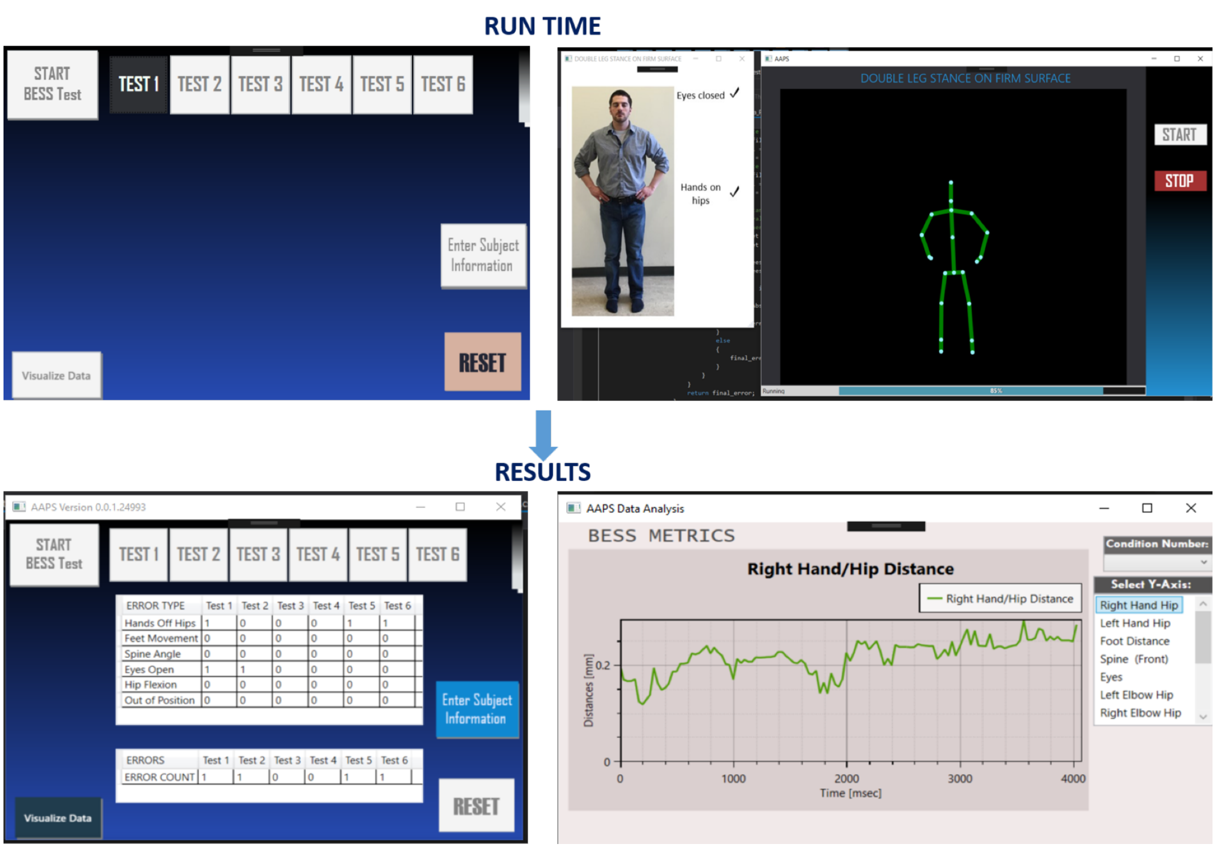


Figure 1: The AAPS Graphical User Interface showing both run-time (top) and results (bottom) screens.

with information regarding the subject's position, joints and eyes detection. This helps the non-trained user in positioning the subject for the test and guarantees that all the necessary parameters are tracked correctly before starting the test. During the test, in each frame, the AAPS extracts two types of data from the Kinect sensor: infrared camera videos, which will be saved in the computer memory for optional off-line analysis; and the subject's joint location and eye data. These will be used, frame-by-frame, to build arrays containing the three metrics that will be then used to evaluate errors, namely relative joint distances, segment angles and eye state. After test completion, these metrics will be used to compute balance errors.

The performance of the Kinect™ 2.0 as a tool to evaluate kinematic variables, as compared to current standard methods, is a subject of great interest. Although several studies have been published in this area, the general trend has been to compare motion capture (MOCAP) systems based on scalar summary measures of some ad-hoc selected metric. Examples from previous work include excursion range, mean or peak displacement, mean velocity, and timing of discrete signal events. While such metrics are commonly studied in biomechanics, they do not adequately quantify the temporal structure of the signals under comparison, and are thus limited in terms of the generalizability of their results. Considering these limitations, it is clear that a more thorough evaluation of Kinect 2.0 raw data performance as a MOCAP tool and its validation against a gold-standard 3D system are needed. Specifically, we have validated the Kinect against a professional Qualisys three-dimensional motion capture system with 12 IR-cameras. In order to better analyze the Kinect-based MOCAP performance in evaluating human kinematics, we chose a complete range of dynamic movements and clinical tests that can be used as broad indicators of functional movements. We acquired data from four healthy subjects in a professional motion analysis laboratory in which signals from two side-by-side Kinects were recorded simultaneously with data from a professional grade Qualisys system. The side-by-side Kinect recordings were made to quantify sensor reliability.

Four subjects (three males, mean age 23) performed a series of movements while being simultaneously tracked by two immediately adjacent Kinect 2.0s and a professional-grade motion capture system (Qualisys, Gothenburg, Sweden). The two Kinects were used to evaluate inter-unit accuracy, and motion tracking results from both systems were compared to the gold standard Qualisys system. The movements and the recording paradigm were specifically designed to facilitate the quantification of errors in tracking joint angles and limb locations relative to all three cardinal planes of the body axis: coronal, sagittal, and transverse. The four subjects were asked to move through a series of postures twice. Each posture was preceded with a large movement such as a T-pose or an overhead reach in order to facilitate time-synchronization of the Qualisys and Kinect systems; these movements were not scored or otherwise included in the results. Three subjects performed a battery of standard clinical tests of dynamic posture, whereas the fourth subject performed the stereotyped postures (e.g. movements restricted to a single plane).

Figure 2 shows representative joint center displacements of head, spine, left hip, and right hip, as measured for a single subject during a sit-to-stand test; data from both Qualisys and Kinect are displayed. This figure illustrates similarities between the joint displacement data are from the two motion capture systems. This figure also underscores the need for multiple similarity metrics, since it is possible to have a high cross correlation but also a high mean squared error. The poorest cross-correlation scores were generally obtained with respect to those axes along which the observed motion was negligible (mediolateral in the case of sit-to-stand). Note also that, in general, tracking between the two systems was less robust in the anteroposterior plane (representing 'depth' away from the Kinect sensor), than in the rostrocaudal plane (vertical) plane.

We used two separate error metrics to describe the performance of the Kinect system relative to the benchmark Qualisys system. First, we calculated cross-correlation coefficients, which effectively describe

how much information one signal can yield about another, but that is generally blind to errors of constant or near-constant offset or bias. Secondly, we calculated the mean-squared errors (MSEs) between the various output signals. MSE measures constant or near constant differences between signals but is blind to signal correlation.

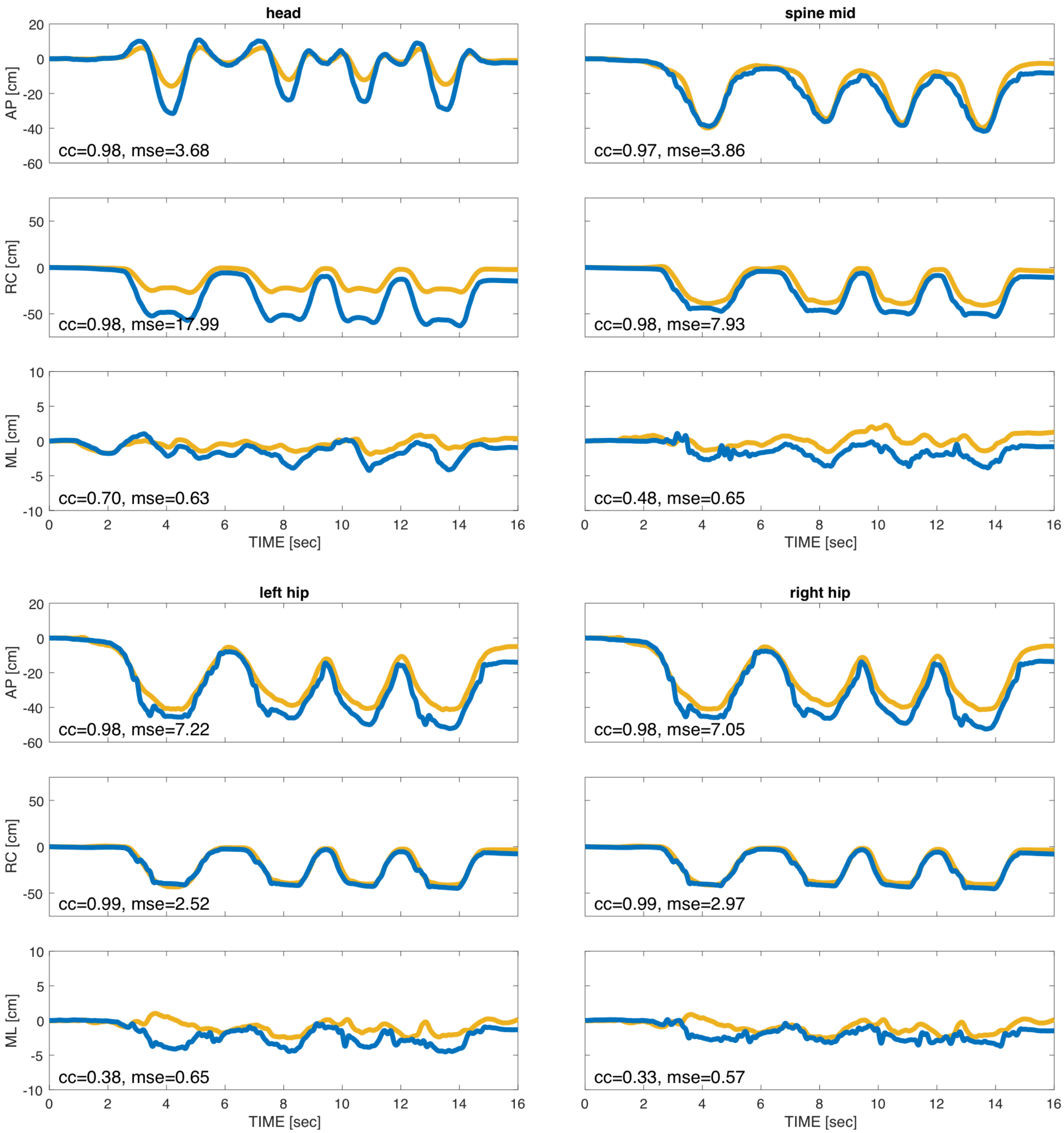


Figure 2: Head, spine middle, left and right hip joint center displacements in cm as derived from both MOCAP systems Qualisys (yellow) and Kinect (blue), during a sit to stand test. The displayed signals are for a single subject and a single trial. Values in the lower left corner of each plot show the cross-correlation coefficients and the mean squared error calculated between the Qualisys and the Kinect displacements over time. ML = Mediolateral, RC = rostrocaudal, AP = anteroposterior

While Figure 2 shows tracking in a specific case, Table 1 summarizes the cross-correlation and mean square error of the 3d movement tracking across 12 different movements. Note that the error depends on the movement and the plane. These results accurately capture, for the first time, the tracking resolution of the Kinect with respect to movements and postures that are relevant to the physical therapy community. Importantly, our observation that the errors vary according to the specific movement have ramifications for how the AAPS is calibrated. Fortunately, the data (which here are only summarized; a full treatment will be presented in our forthcoming journal publication) demonstrate sufficient accuracy to justify using the Kinect as the motion tracking for the AAPS system.

Progress Relative to Goals

At the end of Year 1 (of 3), this project is ahead of schedule and under budget. Expenditures during Year 1 totaled $384,000, versus a budgeted amount of $442,496. The underspending was a results of two factors. First, it took several months to staff up completely. Postdoc Napoli started on 1 November 2015, and Postdoc Glass on 1 January 2016. Although graduate research assistant Ward began work at the start of the project, he only devoted 50% effort until 1 January 2016. Secondly, graduate RA Ward required less tuition than was originally budgeted, because he has completed didactic coursework and is now devoted primarily to research.

Despite being under budget, the project is ahead of schedule. Table 2 shows the status of the Specific Aims and Sub-Aims, relative to the timeline as originally stated in the research proposal. As stated earlier, the baseline AAPS has been completely built and tested, and work human subject evaluation, which wasn't slated to begin until Year 2, is already well under way. We have even made initial progress into feasibility and planning for the xAAPS development, which is the final Aim and the subject of Year 3. Note that, although Aim 1.3 is not entirely complete, we expect it to be closed out by the end of next quarter.

Table 1: Errors in tracking joint displacement. Errors are averaged over all repetitions of all 20 tracked body points. AP = anteroposterior, RC = rostrocaudal, ML = mediolateral

Movement	**correlation**			**error**		
	AP	RC	ML	AP	RC	ML
sit to stand	0.85	0.84	0.67	4.30	4.51	2.63
timed up and go	0.97	0.75	0.83	10.13	4.41	5.07
alternating barbell lunges	0.92	0.80	0.87	9.50	5.40	2.18
overhead squats	0.78	0.86	0.61	4.27	5.72	1.86
marching in place	0.88	0.80	0.92	2.17	2.05	1.86
time to stabilization	0.93	0.89	0.87	6.15	3.54	3.84
shoulder ab/adduction	0.60	0.75	0.65	1.24	1.98	0.98
shoulder flexion/extension	0.66	0.65	0.64	1.95	3.02	1.10
hip ab/adduction	0.71	0.78	0.95	1.85	2.61	2.85
combined hip/knee flexion/extension	0.85	0.87	0.97	1.58	2.24	3.88
combined arm ab/adduction	0.49	0.55	0.56	1.46	4.09	1.76
sagittal/frontal trunk leans	0.78	0.59	0.84	2.16	3.21	3.10

Table 2: Project status relative to timeline originally stated in the research proposal.

Specific Aim 1 – Develop AAPS Baseline System		
Port Image Processing Code to C/C++	1-5 months	100%
Develop User Interface	4-8 months	100%
Develop AAPS for Field Use	7-12 months	75%
Specific Aim 2 – AAPS Calibration and Baseline Evaluation		
Healthy Subject Evaluation	12-18 months	35% (17 subjects complete)
Concussion Subject Evaluation	18-30 months	0%
Mild Musculoskeletal Injury Subject Evaluation	18-30 moths	0%
Specific Aim 3 – AAPS Field Evaluation		
Evaluate use by non-clinician operators	12-15 months	0%
Evaluate AAPS in Field Conditions	14-24 months	0%
Specific Aim 4 – Develop Expanded xAAPS Test		
Determine movements for xAAPS test	18-22	15%
Update AAPS software for xAAPS test	18-30	10%
Evaluate xAAPS test	30-36	0%

What opportunities for training and professional development did the project provide?

This project has provided excellent opportunities for training and professional development, since almost all of the main work has been performed by trainees. Although the co-PIs retain close oversight, day to day operations and planning have been delegated to the postdoctoral fellows, for whom this is excellent professional training. The graduate research assistant has been mentored by both PI Obeid and the Fellows. His responsibilities have included writing software and developing much of the back end mathematics behind the manipulations of the three dimensional mathematics. The two undergraduates (both female; one underrepresented minority) have learned to program, to debug software, and to work use team-based software tools such as bug tracking and distributed version control.

Both postdoctoral fellows and the graduate student have attended research conferences this year and they have all contributed to planning and writing three manuscripts, the first of which will be submit for review within a month.

How were the results disseminated to communities of interest?

Most of Year 1 has been devoted more to technology development and less to dissemination. Even so, the team has made excellent progress in disseminating our work. The team published a paper at the IEEE-EMBS 2016 Annual Conference, which was presented by Dr. Napoli. The team is also preparing three manuscripts, the first of which will be submit for review within one month. These three papers address:

1. Techniques for calibrating the Kinect and using it for motion capture in a physical therapy paradigm
2. BESS test scored using AAPS/Kinect versus motion tracking from professional-grade system
3. BESS test scoring using AAPS versus human scoring

The second two manuscripts are expected to be submit during the second quarter of Year 2.

What do you plan to do during the next reporting period to accomplish the goals and objectives?

During Year 2, we expect the emphasis to be on data collection and analysis. This data collection will occur both in the lab and in the field, in collaboration with Temple ROTC and our military partners. The team will also harden the technology for field use by minimally trained non-medical cadets. During the latter half of the year, we will begin the process of developing the expanded xAAPS system, both in terms of defining movements to be tracked and writing software to track and evaluate those movements.

Impact

Principal project discipline

Although there have been a handful of reports in the literature describing how accurate the Kinect is, none of them have adequately taken into account either the range of 'normal' movements (in a kinematic sense) or the allocation of errors into the three cardinal planes. Such data is critical in order to understand the limits of accuracy that can be expected from Kinect-based systems. By publishing our findings in this area, we are making a fundamental contribution to the Kinect-based motion tracking research community.

Other disciplines

Nothing to report.

Technology transfer

Nothing to report (yet).

Society Beyond Science and Technology

The goal of this project has always been to improve awareness and treatment of concussion by providing a low cost, low complexity way of quantifying degradation in balance ability. Given what is now known about the pervasiveness of concussion and mild brain injury, especially in the armed forces community, this project has the potential to contribute positively to societal health and wellbeing.

Changes/Problems

Changes in approach and reasons for change.

Nothing to report.

Actual or anticipated problems or delays and actions or plans to resolve them.

Nothing to report.

Changes that have a significant impact on expenditures.

Nothing to report.

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents.

Nothing to report.

Products

[1] Napoli A, Glass S, Ward C, Tucker C, Obeid I (2017) "Implementation and validation of a generalized motion capture system using Microsoft Kinect 2.0," in preparation for submission to *Biomedical Signal Processing & Control*

[2] Napoli A, Ward C, Glass S, Tucker C, Obeid I (2016) "Automated Assessment of Postural Stability System," IEEE Engineering in Medicine & Biology Conference, Orlando, FL.

Participants & Other Collaborating Organizations

What individuals have worked on the project?

Name:	Iyad Obeid, PhD
Project Role:	co-Principal Investigator
Person-Months:	3
Contribution:	Dr. Obeid contributed to project design and management, analyzed data, supervised data marshalling, wrote quarterly reports, and contributed to all technical publications.

Name:	Carole Tucker, PhD
Project Role:	co-Principal Investigator
Person-Months:	3
Contribution:	Dr. Tucker contributed to project design and management, IRB preparation, human subject protocol design, data collection, and analysis, and all technical publications.

Name:	Alessandro Napoli
Project Role:	Postdoctoral Fellow
Person-Months:	10
Contribution:	Was responsible for managing all aspects of the software organization and development, and contributed heavily to actual software creation. He managed the graduate RA and the undergraduates, contributed to data collection and analysis, and took a leading role on all technical publications.

Name:	Stephen Glass
Project Role:	Postdoctoral Fellow
Person-Months:	8
Contribution:	Was responsible for managing all aspects of data planning, collection and analysis, including IRB development. He managed junior students, and also developed our analysis of human-versus-Kinect balance scoring analysis. Dr. Glass also took a leading role in all technical publications.

Name:	Christian Ward
Project Role:	Graduate Research Assistant
Person-Months:	5
Contribution:	Was responsible for software development and testing, and developed all 3D vector mathematics. Also worked closely with the undergraduate researchers.

Name:	Orlena Roe
Project Role:	Undergraduate Researcher
Person-Months:	3
Contribution:	Contributed to software testing and development of the graphical interface.

Name:	Elizaveta Ibeme
Project Role:	Undergraduate Researcher
Person-Months:	1
Contribution:	Contributed to software testing and wrote software tools for data analysis.

Has there been a change in the other active support of the PD/PI(s) or senior/key personnel since the last reporting period?

Nothing to report.

What other organizations have been involved as partners?

Nothing to report.

Special Reporting Requirements

See Quad Chart in the Appendix

Appendices

Quad Chart – see next page

Automated Assessment of Postural Stability (AAPS)

Log Number: MR141272
Award Number: W81XWH-15-1-0445

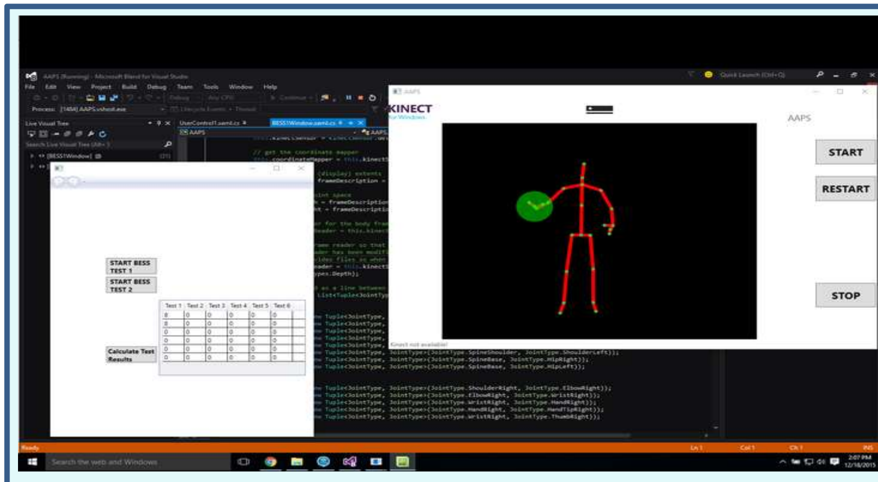
PI: Iyad Obeid & Carole A. Tucker **Org:** Temple University **Award Amount:** $1.36M

Study/Product Aim(s)

- Develop a fully functional proof-of-concept system (AAPS), featuring a complete software suite for automatically administering the Balance Error Scoring System (BESS) test.
- Calibrate the AAPS on healthy, concussion, and musculoskeletal injury subjects.
- Fully field test AAPS to ensure use by non-medical technicians.
- Expansion of AAPS to include dynamic postural tasks.

Approach

We aim to develop, calibrate, and field test a system for quantifying the impact postural and balance injuries using the Microsoft Kinect, an inexpensive motion capture system. The system will administer and score the BESS in field conditions without requiring a medically trained operator. We will expand the BESS to include dynamic tasks (lunge, squat, etc.) to better assess readiness for return to active military duty post mild TBI.



Screenshot showing development of C# code, prototype proof-of-concept GUI interface, and live image capture skeleton.

Timeline and Cost

Activities CY	15	16	17	18
AAPS system development				
Calibrate AAPS (n=50 subjects)				
Field test AAPS				
Expand AAPS – Dynamic tasks				
Estimated Budget ($k)	**$200**	**$500**	**$500**	**$200**

Updated: 30 October 2016

Goals/Milestones

CY15 Goals – System development

✓ Port existing system from Matlab to C/C++ *[100%]*

✓ Develop user interface for automatic test administration *[100%]*

CY16 Goal – Calibration and Field Testing

✓ Determining reference scores for healthy, concussion, and musculoskeletal injury subjects *[25%]*

✓ Comparing performance to gold standard benchmarks *[25%]*

☐ Optimizing design for use by non-medical technicians

CY17 Goal – System expansion

☐ Determining optimal dynamic tasks for assessment

☐ Updating software to handle dynamic task tracking

CY18 Goal – System optimization

☐ Complete expansion and optimize software via patient beta testing

Comments/Challenges/Issues/Concerns

- none

Budget Expenditure to Date

Projected Expenditure: ~$442k

Actual Expenditure: ~$384k